ISOSTASY AND MOUNTAIN RANGES.

By HARRY FIELDING REID.

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The cause of the elevation of mountains has always been a most fascinating subject of study, and we find the earlier geologists giving much attention to it. In the first half of the nineteenth century the prevailing idea was that mountain ranges were due to the upward pressure of liquid lava and that their elevation was closely related to the volcanic forces. As late as the middle of the century Elie de Beaumont upheld this idea with all the prestige of his great authority.

But a more detailed study of the structure of the rocks which make up the mountains led to different conceptions. It was found that the whole mass had been subjected to tremendous compressional forces in a line at right angles to the mountain range. This was shown by the immense folding of the rocks, the existence of thrust-faults and of cleavage and the evident flattening out of fossils; so that the existence of these tangential forces was thoroughly proven. This led then to the idea that mountains owe their origin not to vertical forces, but to the great tangential forces which folded the rock and squeezed it upwards. Professors Heim and Suess in Europe, and Dana, Hall and Le Conte in America, were all very active in developing this point of view, though Dana realized that vertical forces also played some part in the elevation of mountains; but the dominant influence of the tangential forces was recognized in the name *orogenic,* or *mountain-making* forces, which was reserved entirely for them. Without doubt, confidence in the efficiency of tangential forces was greatly strengthened by the fact that these forces could be satisfactorily accounted for by the cooling of the earth; for the cooling is greatest at a short distance below the surface and the exterior layers are subjected to tangential crushing to accommodate themselves to the shrinking interior.

There are great areas of the earth, such as the high plateau regions in the west of the United States, where the rock has been elevated many thousands of feet but without suffering any compression whatever, which makes it quite evident that there are vertical forces which produce many movements in the earth's crust. Mr. Gilbert has given to these forces the name of *epeirogenic,* or *continent-making* forces, to distinguish them from orogenic forces; but we must not forget that epeirogenic forces are apparently alone active in the elevation of certain mountain ranges. The Sierra Nevada, for instance, although its strata are much folded, owes its present elevation to the vertical forces which seem still to be tilting the great block. Mt. St. Elias also seems to have been tilted up by vertical forces without any folding of its strata.

The American geologists showed that a mountain range does not rise haphazard in any part of the earth, but that it appears where there was earlier a great geosynclinal, which had gradually subsided and accumulated sediments to an extraordinary thickness, all of them being laid down in comparatively shallow waters; and it was only after this preparatory step that the foldings and elevation of the mountain range took place.

But there is one important factor to which geologists have not given proper attention, that is, the revelations of the plumb-line. About the middle of the nineteenth century Archdeacon Pratt pointed out that in the south of India the plumb-line was deflected toward the Indian Ocean, and in the north of India, although it was deflected somewhat toward the Himalaya mountains, still the gravitational attraction of these mountains was considerably less than it should have been, if the density of the material in and under them had been the same as in other parts of the earth's crust; and he, therefore, suggested that the oceans were deep because the material under them was heavy, and the mountains were high because the material which composed them was light, and that in general the amount of material under any two equal segments of the earth was the same. But these facts did not make a great impression upon geologists and did not prevent the further advocacy of compression and the consequent accumulation of material as the cause of mountain elevation.

In 1880 Mr. Faye showed that the so-called "anomalies" of gravity would practically disappear if, in reducing observations on land to sea-level, no account were taken of the land mass above sea-level; and if, in reducing observations made on islands in mid ocean, the excess of attraction of the island mass over an equal amount of sea-water were subtracted. This is equivalent to assuming that the continental areas stand up on account of their low densities, but that the small islands are supported by the rigidity of the crust.[1]

In 1889 Major Dutton read a very remarkable paper before the Philosophical Society of Washington,[2] in which he pointed out that the mountain regions were probably continuing to rise as a result of the lightening of their weight by erosional transportation and that regions of deposition near the coasts were probably sinking on account of the added material which they were receiving, and that the forces thus brought into play would set up slow currents from the regions under the sea towards the region under the mountains; and he held that the earth was not strong enough to sustain the weight of great mountain ranges but that these owed their elevation to the fact, as already suggested by Archdeacon Pratt, that they were lighter than the material under the lowlands, or under the oceans; and that there was, therefore a certain equality of weight in the various segments of the earth. He gave to this theory the name of *isostasy,* which has served to give it definiteness ever since. It is to be noticed that Major Dutton considered the elevation of mountains to be due to vertical, and not to tangential forces.

The theory of isostasy has been much discussed by geologists since Major Dutton's paper; many papers have been written on the subject, and the available geological evidence has been invoked in support of, or against, the idea; but it was not until very recently that the real evidence, which lies in the variations of the force of gravity and the deviation of the vertical, has led to definite conclusions.

Mr. Putnam and Mr. Gilbert[3] discussed a series of gravity ob-

[1] "Sur la reduction des observations du pendule au niveau de la mer," *C. R. de l'Acad. des Sciences,* 1880, Vol. 90, pp. 1443–1447.

[2] "Some of the Greater Problems of Physical Geology," *Bull. Philos. Soc. of Washington,* 1889, Volume XI., pp. 51–64.

[3] "Results of a Trans-Continental Series of Gravity Measures," *Bull. Philos. Soc. of Washington,* 1895, Volume XIII., pp. 31–76.

servations made across the United States, which led them to the conclusion that isostasy was true only in so far as the very largest features of the earth's crust, such as the continents and ocean basins, were concerned, but that mountain ranges were at least in part supported by the rigidity of the crust.

When Dr. Nansen drifted across the North Polar basin in the *Fram* he provided pendulums to determine the force of gravity when the ship was frozen in ice; and the discussion of his observations showed that gravity was normal over that basin, or, at least, where his observations were made.[4]

Professor Helmert,[5] in Germany, has done much in the discussion of gravity measures and Dr. Hecker has made some notable voyages and has determined the forces of gravity at sea, over the Atlantic, Indian and Pacific oceans, and over the Black Sea, the results showing that on the whole the force of gravity is normal over these bodies; only in special and limited areas, in the neighborhood of very steep slopes, was any marked anomaly found.[6]

But the most important work which has been done along this line is the work of Dr. John F. Hayford,[7] who, while connected with the United States Coast and Geodetic Survey, discussed in a thorough and able manner the deflections of the vertical at a large number of stations in different parts of the United States, and his results show definitely that over this region isostatic equilibrium actually exists. He has concluded that this is true even for areas as small as a square degree, that is, seventy miles on the side. He believed

[4] "The Norwegian North Polar Expedition of 1893–96," Volume II., Part VIII., Results of the Pendulum Observations, by E. O. Schiotz.

[5] "Hohere Geodesie," Leipzig, 1880.

[6] "Bestimmung der Schwerkraft auf dem Atlantischen Ozean," *Veröff. des König. Preuss. Geodet. Instit.*, Neue Folge, No. 11. "Bestimmung der Schwerkraft auf dem Indischen und Groszen Ozean," *Veröff. des Zentral Bureaus der Internat. Erdmessung,* Neue Folge, No. 18. "Bestimmung der Schwerkraft auf dem Schwarzen Meere," same, No. 20.

[7] "The Geodetic Evidence of Isostasy, etc.," *Proc. Washington Acad Sci.*, 1906, Vol. VIII., pp. 25–40. "The Earth a Failing Structure," *Bull. Philos. Soc.*, Washington, 1907, Vol. XV., pp. 57–74. "The Figure of the Earth and Isostasy," United States Coast and Geodetic Survey, 1909. "Supplementary Investigation in 1909 on the Figure of the Earth and Isostasy," same, 1910. "The Relation of Isostasy to Geodesy, Geophysics and Geology," *Science,* February 10, 1911.

that the earth is not strong enough to sustain an added thickness of more than about two hundred and fifty feet of rock over an area as large as a square degree without slowly yielding. The stations where the observations were made are scattered over various parts of this country, on the eastern coast, in the Appalachian mountain range, in the region of the Great Lakes, near the Gulf of Mexico, in the great plains of the Mississippi basin, on the great elevations of the Rocky Mountains, the plateaux of Utah, the Sierra Nevada mountains and the Pacific coast, regions exhibiting a great variety of topographic forms and differing greatly as to geologic activity. Whatever movements may be going on in the Rocky mountains, and in the region between them and the Atlantic ocean, are certainly very small; whereas to the west, and particularly in the state of California, the movements seem to be very active. The eastern edge of the Sierra Nevada received additional elevation at the time of the Owens Valley earthquake in 1872, and the comparatively frequent earthquakes in the Sierras and the Coast ranges make it quite possible that these mountains are now being elevated as actively as at any time in their history. In view of the great variety of the country in which the stations were located, both as to topography and geologic activity, in view of the great amount of material being continually eroded from one region and deposited in another, thus tending to overthrow the isostatic equilibrium, and in view of observations in other parts of the world, we are driven, with Dr. Hayford, to the conclusion that isostasy is not an accidental condition existing at the present time within this country, but is due to the fact that the earth yields plastically to the long continued action of even small forces. We feel justified, therefore, in believing that isostatic equilibrium exists in other parts of the world and existed in other geologic ages, and in saying that the whole earth is, and always has been in isostatic equilibrium.

This conclusion carries with it many important consequences and has a very direct bearing on the theories of the origin of mountain ranges; for it tells us that every segment of the earth, having an equal area of surface and with its apex at the center, contains the same amount of material, which it is impossible either to increase

or decrease. If by erosional transportation a large quantity of material is removed from a high land and deposited in the oceans, then the increase of weight under the ocean and the decrease under the mountains will, as Major Dutton explained, set up a subterranean counter flow, which will restore the equality of material in the segments. If by the exercise of tangential forces a portion of the earth's crust is compressed and folded and the quantity of material in the segment thus increased, the added weight will cause a slow sinking of the region and material will flow out from below and reduce the mass of the segment to its proper value. Indeed, the folding up of the rock by tangential pressure would not elevate a mountain range, but would cause the folded region to sink; not, however, necessarily below its former level.

When we consider the origin of the mountain ranges the theory of isostasy requires that all hypotheses, which call for more than the normal amount of material in any segment, be excluded. The folding of rock under tangential forces, and the increase of material by subterranean flow are necessarily debarred. Dana noticed that the great mountain ranges of the world were opposite the great oceans and, in some cases, were opposite the great depths of the oceans. The inference was natural that material was taken from the ocean bed, increasing its depth and added to the land increasing its height; but the theory of isostasy forbids this inference. He also suggested that the segments of the earth forming the oceans were sinking more rapidly, as the earth cooled, than the segments forming the continents and also that they were stronger; so that they compressed the continents, folding the rock and making mountain ranges around their borders. Besides other objections to this idea, the theory of isostasy excludes it on account of the increased material required in the land segment. Professor Charles Davison[8] has suggested that the oceans owe their existence to the stretching and consequent thinning of the strata below them, but the theory of isostasy does not permit the withdrawal of material from the ocean

[8] "On the Distribution of Strain in the Earth's Crust resulting from Secular Cooling, with special reference to the Growth of Continents and the Formation of Mountain Chains," *Phil. Trans. R. S.*, 1887, Vol. 178(A), pp. 231–242.

bottoms. Sir George Darwin[9] has suggested that the continental areas of the earth may be due to elevations caused by the differential retarding effect of lunar tidal action. But the theory of isostasy tells us that they could not have maintained themselves unless they were especially light; and in this case they would have existed independently of the tidal forces. Although these elevations, or "wrinkles," as Sir George Darwin calls them, might have been distorted by the different tidal effects in different latitudes, their original meridional direction still requires explanation.

The foldings and contortions of the rock have been so intimately associated, in the minds of geologists, with mountain ranges, that a low-lying region of folded rock has been looked upon as the remains of a mountain range removed by erosion; but as mountains are not due to rock folding, this inference may be entirely wrong.

Only a few of the consequences of the theory of isostasy have been mentioned; but the principle is of such fundamental importance that it will surely exercise a strong influence over our future theories, and will be applicable in directions not now suspected. Unfortunately, it does not tell us definitely what is the cause of the elevation of mountains and plateaux; but it limits our inquiries by excluding all theories which assume the addition of matter to a segment. It tells us, quite definitely, that the elevation of mountains, or the depression of the oceans, must be due to vertical forces brought about by a decrease, or increase, in the density of the material under these regions. According to it, the mountains are high because their material is light; and as geological history tells us that the mountains have not always existed, we must conclude that they were elevated by an expansion of the material in and under them. And the great deeps of the oceans are deep because the material under them is dense and they have become deep by an increase in the density of this material. Since all mountain areas are being lowered by active erosion and many of the great ocean deeps are being filled by depositions, the great heights of the former must be due to the fact that they are still in the process of elevation or that they have only

[9] "Problems connected with the Tides of a Viscous Spheroid," *Phil. Trans. R. S.*, 1879, Vol. 170, p. 589.

recently been raised; and the great depths of the latter to the fact that they are in the act of sinking, or have only recently sunk. As the centres of the great majority of strong earthquakes are along the boundaries of high mountain ranges, or of great ocean deeps, it seems most probable that the forces which have produced these very interesting features of the earth's surface are still in active operation.